

# Dimensioning and Computational Results for Wide-Area Broadband Networks with Two-level Dynamic Routing\*\*

D. MEDHI<sup>†</sup> and C.-T. LU<sup>†</sup>, *Nonmembers*

**SUMMARY** The Virtual Path (VP) concept is one of the versatile features of ATM/B-ISDN. Using the VP concept, a bundle of virtual circuits can be grouped together between any two switching nodes in the network. Further, the VP bandwidth and routing can be dynamic. Building on this idea, a dynamically reconfigurable, dynamic call routing wide area (backbone) broadband network concept is proposed. Specifically, this provides dynamism at two levels: at the VP level and at the connection level. For an incoming connection request, at most two logical virtual path connections (VPCs) are allowed between the origin and the destination; these logical VPCs are defined by setting virtual paths links (VPLs) which are, in turn, physically mapped to the transmission network. Based on the traffic pattern during the day, the bandwidth of such VPCs and their routing, as well as call routing, changes so that the maximum number of connection requests can be granted while maintaining acceptable quality of service (QoS) for various services. Within this framework, we present a mathematical model for network design (dimensioning) taking into account the variation of traffic during the day in a heterogeneous multi-service environment. We present computational results for various cost parameter values to show the effectiveness of such networks compared to static-VP based networks in terms of network cost.

*key words:* Broadband Networks, Dynamic Routing, Network Design Models, Optimization Algorithms, Virtual Path concept

## 1. Introduction

Asynchronous Transfer Mode (ATM) is emerging as the platform for high-speed networks where broadband services with varying bandwidth and traffic requirements will be provided [7], [10]. In an ATM/B-ISDN Network, traffic can be considered at the Virtual Path (VP) level, the call level, the burst level and the cell level [12]. Discussion on control issues at different levels can be found, for example, in [17]. A connection-oriented transport mechanism is to be used for ATM networks. This means a virtual connection is required to be set up between the origin and the destination for a connection request. The call then uses this connection. There are two operational steps: in call setup, network resources are checked before the connection is allowed; once the call

is accepted, in the second step network traffic management monitors the traffic status and performs a policing function to ensure that resources are properly used and, accordingly, controls can be applied at burst/cell levels to satisfy quality of service (QoS). Although there has been a considerable amount of literature devoted to congestion control at the burst/cell level for high speed networks in recent years, there have been very few works in the area of network routing for better management/utilization of wide area broadband networks. It is our opinion that the use of effective routing schemes can alleviate congestion problems and reduce overburdening congestion control schemes at cell/burst level.

In this paper, we propose routing at two levels: at the VP level and at the call level. Using the VP concept, a bundle of virtual circuits can be grouped together between any two switching nodes in the network. Further, the VP bandwidth and routing can be dynamic. Building on this idea, we are proposing a dynamically reconfigurable, dynamic call routing concept for wide area (backbone) broadband networks. Given this context, we present an optimization model for network design, and discuss possible roles of dynamic VP bandwidth/routing as well as call routing in case of overload in the network.

We first start by illustrating the differences between a VP-based traffic network and a transmission network for broadband networks. The traffic network is connected by ATM switching nodes where various traffic such as voice, data and video services are provided; the transmission network is connected by ATM cross-connect systems (nodes) [11], [18], [24], [27]. Following the specification by ATM forum [1], we use the following terminology: ATM cross connects provide virtual path switching function while ATM switching nodes act as virtual path terminators. The connection between two ATM switching nodes can be provided using virtual path connections (VPC). Since it is possible to have multiple VPCs for the same pair of switching nodes [1, p. 94], we use the term l-group to indicate this logical grouping of these VPCs between two switching nodes since the ATM forum specification does not define this entity. Two ATM cross-connect nodes can have a Virtual Path Link (VPL) defined between them. Again, it is possible to define multiple VPLs between two cross-connect nodes which is provided on a physical link (p-

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<sup>†</sup>The authors are with the Department of Computer Networking University of Missouri-Kansas City, 5100 Rockhill Road, Kansas City, MO 64110 USA.

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link). Note that l-group is the same as VPC if there is only one VPC defined between a pair of switching nodes; similarly, p-link is the same as VPL if there is only one VPL defined between a pair of cross-connect nodes.

Now consider Fig. 1. The 6-node switched traffic network (Fig. 1b) has the underlying physical network as shown in Fig. 1a. We will assume for this discussion that only a single VPC is defined for an l-group and one VPL is defined for a p-link. In the traffic network, the logical connectivity is shown by VPCs connecting the switching nodes (denoted by circles); in the transmission network, the actual physical connectivity is shown between cross-connect nodes (denoted by squares) connected by VPLs. We assume here that each ATM switching node is co-located with a cross-connect node (although this is not necessary). Assume further that the traffic network has dynamic call routing capability [14] and uses at most two VPCs to connect a call. In this set of figures, assume also that the VPC between switching nodes 2 and 4 are physically connected on the transmission network through the cross-connect nodes 2-3-4; similarly, the VPC between switching nodes 1 and 4 uses the transmission path through the cross-connect nodes 1-2-3-4.

Consider now a call between switching nodes 1 and 4. This call may try to use free VPC capacity, if available, on the direct l-group 1-4 (which physically takes the path through the cross-connects 1-2-3-4); if the call can not find any free VPC capacity on the direct l-group, it may try to switch via, say, the switching node 2; in this case, available VPC capacities on the two l-groups 1-2 and 2-4 will be sought. If we assume that the call can be connected by switching via 2, then an appropriate VPC capacity between switching nodes 1 and 2 (which is physically cross-connected on 1-2), and between switching nodes 2 and 4 (which is physically cross-connected on 2-3-4) will be used for this call; this call uses different VPCs from the one which is for the direct l-group 1-4 that is physically cross-connected on 1-2-3-4 (without entering switches at 2 and 3); although both traffic paths take the same physical links.

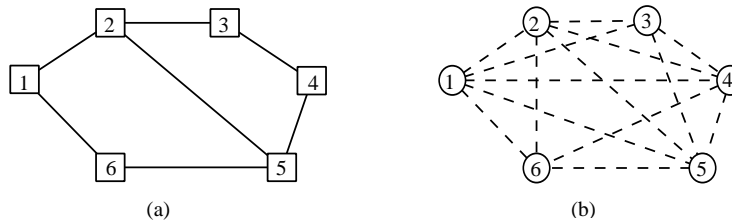
Now consider the issue of traffic demand in the network. It is well-known that the traffic demand (call-attempt rate) keeps varying depending on the time of the day (other variations due to unusual factors are also possible). Now suppose that based on the traffic demand at a certain time during the day, VPCs are set up in the network between switching nodes and to meet grade-of-service/quality of service, calls are direct or alternate routed appropriately. Now, if the traffic demand changes significantly an hour later, then the VPCs as set up may not provide the grade-of-service for the new traffic demand thus requiring reconfiguration of VPCs (and bandwidth) – obviously, this reconfiguration will be possible only if there is sufficient capacity in the transmission network as well as port capacity

at the switches and cross-connect nodes. We use this premise to consider network dimensioning both at the VPC network and transmission level network in an integrated framework by considering multiple traffic hour demand (due to load variation during the day) and dynamic network reconfigurability.

There has been a considerable amount of work done on dimensioning for various types of dynamic call routing for single-service (voice) circuit-switched networks and their advantages have been quantified [3], [5], [9], [14], [20], [25], [32]; and some work on considering (single-service) switched and cross-connect networks together has also been addressed [4], [15], [22], [29], primarily for single-service networks to address network survivability.

Broadband networks based on ATM, however, provide flexibility through bandwidth unit granularity and virtual paths. Depending on the type of service, the peak rate for the service need not be allocated at the time of connection for all service type. Further, it is possible to have dynamic virtual path routing with the flexibility of variable bandwidth. Thus, the capacity for virtual circuit connections required between two switching nodes is not required to be provided on a static bandwidth with fixed path basis; further, the granularity at VP-level can be fine-grained leading to assuming the VP-level capacity to be of continuous unit rather than in discrete modular units as required for circuit-switched networks. However, modularity is still needed in the transmission networks and also for switching ports.; the concept of VPC can be used to define a *logical* l-group between origin and destination ATM switching nodes, where the bandwidth for the VPC and how the VP is routed can be dynamic, thus providing dynamic reconfigurability of networks. Further, the use of VPC in B-ISDN simplifies call processing and reduces connection establishment time as there is no need to do additional processing at the intermediate nodes at the time of the request for connection [1], [6]. For example, in Figs. 1, having a VPC between switching nodes 1 and 4 reduces the connection establishment time as compared to node processing at intermediate switching nodes 2 and 3. In [24], Logothetis and Shioda have presented centralized VP bandwidth allocation scheme for a similar architecture. For other benefits the VP concept, see, for example, [2], [6], [17], [21], [31], [34], [35].

Recently [27], we have considered a direct (single) virtual path connectivity idea using VPC between switching nodes with dynamic bandwidth control and changing VPC routing at different times of the day (with fixed call routing) and have presented such a network from a network planning and management perspective; furthermore, we have shown [26] for some example networks (extracted from an actual network) that dynamic VPC based networks design can save 10% to 14% compared to static VPC routed networks while providing the same quality-of-service. Dimension-



**Fig. 1** (a) Example of a 6-node ATM transmission network, (b) Example of the associated 6-node ATM traffic network (○ – switching node, □ – cross-connect node)

ing have been addressed to some extent for ATM/high speed networks [13],[23]; dynamic call routing in the presence of static virtual path has also been presented [16],[19],[28],[30]; however, these and the references listed earlier do not address the two level routing dynamism for dynamically reconfigurable broadband networks that we are considering here nor do they address network dimensioning for such networks when multiple traffic classes are offered.

## 2. Dimensioning

### 2.1 Framework

The basic framework of a *dynamically reconfigurable, dynamic call routing* (DRDCR) network is the following:

There is (possibly) an l-group between each origin and destination ATM switching nodes in the wide-area traffic network by defining a VPC, possibly multiple VPCs for different traffic types; the VPC may be set up on the transmission network using ATM cross-connect nodes using VPLs on p-links. A call request between an origin and destination for a traffic class may try to see if there is any free capacity left on the direct VPC between them to provide adequate QoS for this traffic class; if not, then dynamically seek up to maximum two VPC segments (for this traffic class) by switching via another ATM switch to connect the call subject to availability of capacity on these two VPCs to provide adequate QoS for this connection. To maintain pairwise and traffic type quality-of-service, VPC bandwidth and routing are changed from time to time during the day resulting in reconfiguration of the traffic network.

We are proposing the above scenario based on the benefit of dynamic call routing (with fixed circuit routing in the transmission network) pointed out by various researchers and our own work on dynamically reconfigurable networks (with fixed call routing) [26],[27]. The proposed framework is the next logical step where we look at the marriage of these two ideas to provide an

efficient network. It should be understood that VPC bandwidth/routing updates are slower than call routing. By limiting a maximum of two VPC segments for each connection, there is still a need to do processing during connection establishment in at most one intermediate switching node; this would not increase the connection establishment time considerably (compared to the direct VPC); yet this provides better connection request completion rate than all calls being routed on single VPC under normal and overloaded network operating conditions. The trunk reservation [36] concept for traffic networks can also be extended to the VPC capacity reservation concept on the transmission network for network stability; additionally, service protection through admission control may also be needed [30]. For simplicity of management of the network, our view is to allow statistical multiplexing of virtual circuits *within* a VPC for a traffic class; however, various VPCs may be deterministically (non-statistically) multiplexed within an l-group (and hence on transmission links); this view is taken by us in [26],[27] where we define the notion of similar traffic quality-of-service (STQoS) class where traffic with similar characteristics and QoS requirements are defined as one service class or type. Statistical multiplexing of VPCs are not considered here to reduce the complexity of network control since deterministic multiplexing of VPCs allows us to control each STQoS class independently for the connections for that class without needing to worry how cells from other STQoS classes might interfere with this class. While dynamic call/connection routing was not considered in [26],[27], this is now addressed in the present paper. Let us visit Fig. 1a again. A VPC may be defined with a certain amount of capacity between switching nodes 1 and 4 which uses the VPLs on 1-2, 2-3, 3-4 at a certain time of the day, while the same VPC at another time of the day may have different capacity and/or may take a different path by using, say, VPLs on 1-6, 6-5, 5-4. This is of course dictated by the change in load pattern and successful completion of connection request between an origin and destination ATM switches, and availability of transmission network capacity.

## 2.2 A Mathematical Model

Before we present the model, we first describe the notations:

$\mathcal{K}$  Set of traffic node pairs

$\mathcal{L}$  Set of l-groups among the switches

$\mathcal{H}$  Set of traffic load periods during a day

$\mathcal{M}$  Set of p-links in the physical network

$\mathcal{S}$  Set of services types

$\bar{\mathcal{P}}_k^{sh}$  Set of (candidate) at most two VPC-segment traffic paths for service type  $s \in \mathcal{S}$  for pair  $k \in \mathcal{K}$  in hour  $h \in \mathcal{H}$

$\hat{\mathcal{P}}_\ell^{sh}$  Set of candidate VPL paths for logical VPC for service type  $s$  in hour  $h$  defined on l-group  $\ell$

$x_{kj}^{sh}$  Flow variable in traffic network – amount of flow on traffic path  $j \in \bar{\mathcal{P}}_k^{sh}$  for service type  $s$  for node pair  $k$  in hour  $h$  (variable)

$u_{kj}^{sh}$  Upper bound on flow corresponding to  $x_{kj}^{sh}$

$y_\ell^{sh}$  Bandwidth needed on the VPC for service type  $s$  in hour  $h$  on l-group  $\ell \in \mathcal{L}$  (variable)

$z_{li}^{sh}$  Flow on physical path  $i \in \hat{\mathcal{P}}_\ell^{sh}$  for service type  $s$  in hour  $h$  for l-group  $\ell \in \mathcal{L}$  (variable)

$v_{li}^{sh}$  Upper bound on flow corresponding to  $z_{li}^{sh}$

$w_m$  Maximum number of high capacity units required on p-link  $m \in \mathcal{M}$  (variable)

$t_\ell$  Overall capacity need on l-group  $\ell$  for all VPCs on this group for any load hour (variable)

$\alpha$  Capacity of a high capacity unit on l-groups

$\beta$  Capacity of a high capacity unit on p-links

$e_\ell$  Cost of a high capacity unit on l-group  $\ell \in \mathcal{L}$

$c_m$  Cost of a high capacity unit on p-link  $m \in \mathcal{M}$

$\delta_{kj}^{sh\ell}$  Entries for arc-path incidence matrix for the traffic network – 1 if traffic path  $j$  for service type  $s$  for node pair  $k$  uses l-group  $\ell$  in hour  $h$ , 0 otherwise

$\gamma_{li}^{sh m}$  Entries for arc-path incidence matrix for the transmission network– 1 if the transmission path  $i$  for the VPC for service type  $s$  in hour  $h$  on l-group  $\ell$  uses the p-link  $m$

$A_k^{sh}$  Traffic amount for service type  $s$  in  $h$  for pair  $k$

$d(A_k^{sh}, T_s, QoS_s)$  Bandwidth required for traffic amount  $A_k^{sh}$  for service type  $s$  with traffic descriptor  $T_s$  and quality of service requirements  $QoS_s$  (in  $h$  for pair  $k$ ; more described later)

We now present a mathematical model for network dimensioning (sizing) of DRDCR broadband networks:

$$\min_{\{x,y,z,w,t\}} \sum_{\ell \in \mathcal{L}} e_\ell t_\ell + \sum_{m \in \mathcal{M}} c_m w_m \quad (1a)$$

subject to

$$\sum_{j \in \bar{\mathcal{P}}_k^{sh}} x_{kj}^{sh} = d(A_k^{sh}, T_s, QoS_s), \quad s \in \mathcal{S}, k \in \mathcal{K}, h \in \mathcal{H} \quad (1b)$$

$$\sum_{k \in \mathcal{K}} \sum_{j \in \bar{\mathcal{P}}_k^{sh}} \delta_{kj}^{sh\ell} x_{kj}^{sh} \leq y_\ell^{sh}, \quad \ell \in \mathcal{L}, s \in \mathcal{S}, h \in \mathcal{H} \quad (1c)$$

$$\sum_{s \in \mathcal{S}} y_\ell^{sh} \leq \alpha t_\ell, \quad \ell \in \mathcal{L} \quad (1d)$$

$$\sum_{i \in \hat{\mathcal{P}}_\ell^{sh}} z_{li}^{sh} = y_\ell^{sh}, \quad \ell \in \mathcal{L}, s \in \mathcal{S}, h \in \mathcal{H} \quad (1e)$$

$$\sum_{\ell \in \mathcal{L}} \sum_{s \in \mathcal{S}} \sum_{i \in \hat{\mathcal{P}}_\ell^{sh}} \gamma_{li}^{sh m} z_{li}^{sh} \leq \beta w_m, \quad h \in \mathcal{H}, s \in \mathcal{S}, m \in \mathcal{M} \quad (1f)$$

$$0 \leq x_{kj}^{sh} \leq u_{kj}^{sh}, \quad j \in \bar{\mathcal{P}}_k^{sh}, s \in \mathcal{S}, k \in \mathcal{K}, h \in \mathcal{H} \quad (1g)$$

$$y_\ell^{sh} \geq 0, \quad \ell \in \mathcal{L}, h \in \mathcal{H}, s \in \mathcal{S} \quad (1h)$$

$$0 \leq z_{li}^{sh} \leq v_{li}^{sh}, \quad i \in \hat{\mathcal{P}}_\ell^{sh}, \ell \in \mathcal{L}, s \in \mathcal{S}, h \in \mathcal{H} \quad (1i)$$

$$t_\ell \geq 0 \text{ and integer}, \quad \ell \in \mathcal{L} \quad (1j)$$

$$w_m \geq 0 \text{ and integer}, \quad m \in \mathcal{M} \quad (1k)$$

In this model, (1b) refers to determination of flow on one or two segment VPCs to satisfy traffic requirement for a particular service type for a given quality-of-service; (1c) is to determine the capacity of the VPC at various time of the day needed for each service type while (1d) is to determine how much  $\alpha$ -modularized VPC capacity needed needed on an l-group to meet traffic demand at any time of the day for all service types – modularization is used here since VPCs may be bundled so as to determine modular port requirements at switching nodes (see results section). In, (1e) we show how the VPC bandwidth for each service type and load hour for each l-group (as obtained from (1c)) should be physically routed among various dynamically reconfigurable paths at different time of the day. (1f) then shows the actual capacity required on high capacity transmission links [subject to  $\beta$ -modularization] to cover for varying bandwidth VPs for all service types. The rest of the constraints (1g-1k) are bound constraints on variables and also to indicate which variables take integer values. The cost for the network as shown in (1a) is the cost due to capacities on l-groups

as well as capacities on physical links (including any cost for termination ports, see results section).

The function,  $d(A, T, QoS)$ , to determine the bandwidth required for different services types and QoS can take different forms depending on the service class. We briefly discuss it here; if a homogenous traffic type (with Poisson call arrival) requires a real-time circuit-mode [constant bit rate (CBR)] connection (e.g, class-A traffic in B-ISDN), then we can use  $A = a, T = R, QoS = GoS = 1\%$  call blocking, where  $a$  is the offered load in erlangs and  $R$  is the peak rate bandwidth required for each connection, GoS stands for the grade-of-service. In this case, the bandwidth requirement can be computed using an approximation as used in [25], [33] for single-service networks. Similarly, an approximation given for multiple traffic types under loss mode with differing bandwidth requirement per call as given in [28] may be used to define a service class in our present framework, or these traffic types may be classified into different service classes depending on network providers' operational need and complexity. In [26], we also discuss how variable bit rate (VBR) traffic [a class-B traffic in B-ISDN] may be defined as another traffic class – only thing this requires is a specific formula for  $d(\dots)$  without needing to entirely change model (1). Obviously, formula for  $d(\dots)$  for all emerging service classes are not known at this time – as we understand more about any emerging traffic types we would be able to define new service classes and develop new formulae.

### 3. Computational Approach

Note that model (1) is a large-scale mixed integer linear optimization problem with the two sets of capacity variables taking integer values while the flow variables take real values. We have developed a sequential approximation of model (1) by looking at the problem structure to effectively handle such a large scale problem. In this approach, we take advantage of the dual-level of traffic and transmission networks, and our procedure works by determining the capacity needed first for the traffic network. Thus, we first solve sub-model (2) for the variables  $x, y, t$ :

$$\min_{\{x, y, t\}} \sum_{\ell \in \mathcal{L}} e_{\ell} t_{\ell} \quad (2a)$$

subject to

$$\sum_{j \in \mathcal{P}_k^{sh}} x_{kj}^{sh} = d(A_k^{sh}, T_s, QoS_s), \quad s \in \mathcal{S}, k \in \mathcal{K}, h \in \mathcal{H} \quad (2b)$$

$$\sum_{k \in \mathcal{K}} \sum_{j \in \mathcal{P}_k^{sh}} \delta_{kj}^{s\ell h} x_{kj}^{sh} \leq y_{\ell}^{sh}, \quad \ell \in \mathcal{L}, s \in \mathcal{S}, h \in \mathcal{H} \quad (2c)$$

$$\sum_{s \in \mathcal{S}} y_{\ell}^{sh} \leq \alpha t_{\ell}, \quad \ell \in \mathcal{L} \quad (2d)$$

$$0 \leq x_{kj}^{sh} \leq u_{kj}^{sh}, \quad j \in \bar{\mathcal{P}}_k^{sh}, s \in \mathcal{S}, k \in \mathcal{K}, h \in \mathcal{H} \quad (2e)$$

$$y_{\ell}^{sh} \geq 0, \quad \ell \in \mathcal{L}, h \in \mathcal{H} \quad (2f)$$

$$t_{\ell} \geq 0 \text{ and integer}, \quad \ell \in \mathcal{L} \quad (2g)$$

Note that we keep the variables  $y_{\ell}^{sh}$  in sub-model (2) which gives us the VPC requirements for different service classes and load hour on an l-group. Since this amount dynamically varies depending on the load, we would accordingly like to set up paths in the transmission network for each service classes. Thus, the solution  $\bar{y}_{\ell}^{sh}$  from sub-model (2) becomes the *input* as the demand for the transmission network in the sub-model (3) given below to determine transmission capacity:

$$\min_{\{z, w\}} \sum_{m \in \mathcal{M}} c_m w_m \quad (3a)$$

subject to

$$\sum_{i \in \hat{\mathcal{P}}_{\ell}^{sh}} z_{li}^{sh} = \bar{y}_{\ell}^{sh}, \quad \ell \in \mathcal{L}, s \in \mathcal{S}, h \in \mathcal{H} \quad (3b)$$

$$\sum_{\ell \in \mathcal{L}} \sum_{s \in \mathcal{S}_k} \sum_{i \in \hat{\mathcal{P}}_{\ell}^{sh}} \gamma_{li}^{sh m} z_{li}^{sh} \leq \beta w_m, \quad h \in \mathcal{H}, s \in \mathcal{S}, m \in \mathcal{M} \quad (3c)$$

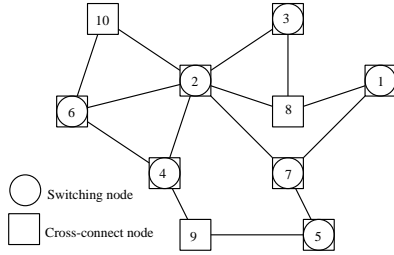
$$0 \leq z_{li}^{sh} \leq v_{li}^{sh}, \quad i \in \hat{\mathcal{P}}_{\ell}^{sh}, \ell \in \mathcal{L}, s \in \mathcal{S}, h \in \mathcal{H} \quad (3d)$$

$$w_m \geq 0 \text{ and integer}, \quad m \in \mathcal{M} \quad (3e)$$

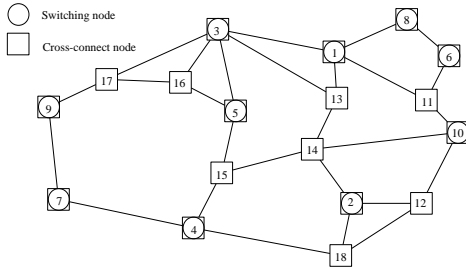
Note that both sub-models (2) and (3) are also mixed integer programming models; however, they are of much smaller scale compared to model (1). Further, this decomposition allows us to compare our DRDCR framework to a dynamic call routing network with only static virtual path notion which is discussed in the next section.

### 4. Computational Results

For computational work, we consider three network cases; the topological view of these networks are given in Figs. 2, 3 and 4. Since, we would like to demonstrate the effectiveness of DRDCR framework, we consider three service classes for simplicity where the first two service classes are CBR voice traffic and CBR video traffic, the third traffic class is VBR voice traffic; these are labeled service class one, two and three, respectively. We use the values  $R_1 = 64\text{Kbps}$  and  $R_2 = 384\text{Kbps}$  for the service classes one and two. For the third class, i.e., for VBR voice traffic, traffic is assumed to be based on on-off sources and fluid-flow approximation is used for obtaining the demand requirement (see service type one in [26]). Connection-level blocking GoS for all three classes are set to 1% blocking. We have considered three traffic load hours to consider variations of traffic during a day. The modular values for  $\alpha$  and  $\beta$  are each set to DS1 ( $\approx 1.544$  Mbps) rate. For cost coefficients,  $e_{\ell}$  and  $c_m$ , we use



**Fig. 2** Topology of EN-1 (7 ATM switching nodes, 10 ATM Cross-connect nodes)



**Fig. 3** Topology of EN-2 (10 ATM switching nodes, 18 ATM Cross-connect nodes)

four parameters (two each) to reflect termination cost as well as distance cost:

$$e_{\ell} = 2\eta + \zeta D_{\ell}$$

$$c_m = 2\theta + \mu D_m$$

where

$\eta$  port termination cost (for an  $\alpha$ -module) in switches

$\zeta$  per unit logical distance cost in the traffic network

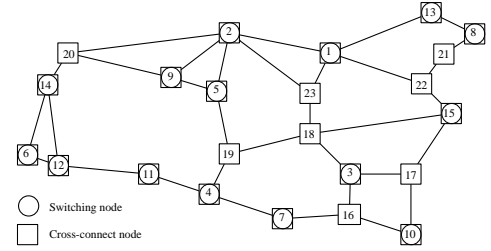
$\theta$  port termination cost (for a  $\beta$ -module) in cross-connect nodes

$\mu$  per unit physical distance cost in the transmission network

$D_{\ell}$  logical distance between switches for l-group  $\ell$

$D_m$  physical distance between cross-connect nodes for p-link  $m$ .

The parameter set  $\{\eta, \theta, \zeta, \mu\}$  allows us to do a sensitivity study for different cost parameter values and see impact on the network cost; further, we can do cost comparison of DRDCR cost with a dynamic call routing but static VP environment (labeled: staticNetCost in Tables). staticNetCost is obtained by solving model (2) and then doing a shortest-distance routing for maximum VP bandwidth required on the transmission network. For the bounds on the path flow variables in the traffic network, a 90% of demand is imposed to limit



**Fig. 4** Topology of EN-3 (15 ATM switching nodes, 23 ATM Cross-connect nodes)

**Table 1** Results for various cost parameter values for EN-1

$\{\eta, \theta, \zeta, \mu\}$	DRDCR-cost	staticNet-Cost	% cost increase
{100,50,0,1}	3705144	4089984	10.39%
{100,75,0,1}	4031640	4535184	12.49%
{100,50,0,0.1}	1712244	1970678	15.09%
{100,50,1,1}	5070528	5398656	6.47%
{100,75,1,1}	5397024	5836656	8.15%
{100,50,0.1,1}	3841688	4187120	8.99%
{100,50,0.1,0.1}	1848788	2094642	13.30%

**Table 2** Results for various cost parameter values for EN-2

$\{\eta, \theta, \zeta, \mu\}$	DRDCR-cost	staticNet-Cost	% cost increase
{100,50,0,1}	18803304	24046896	27.89%
{100,75,0,1}	20162232	25819296	28.06%
{100,50,0,0.1}	6635601	7983969	20.32%
{100,50,1,1}	29161581	33499461	14.88%
{100,75,1,1}	30526293	35255061	15.49%
{100,50,0.1,1}	19898225	23919185	20.21%
{100,50,0.1,0.1}	7730156	8856792	14.57%

the flow on the direct VPC to a maximum of 90% of the demand as given by  $d(\cdot, \cdot, \cdot)$  — this is to reflect the observation that typically in a dynamic call routing network, under normal operating conditions approximately 90% of the calls are direct routed while the rest are alternate routed. We have used this heuristic rule here; obviously, our model allows us to use under bound as deemed appropriate by a network designer. For the traffic networks, the path set  $\bar{\mathcal{P}}$  considers all the maximum two-link traffic paths (including direct path); in the transmission network, a  $k$ -shortest path generator is used to generate five paths for each end-points. All the cost results are shown in Tables 1, 2 and 3 for the three networks considered here. (We note the we have also done runs with seven paths generated and found that the cost decrease compared to five-paths case is less than 0.4%). Models (2) and (3) are solved using mixed integer program solver from CPLEX [8].

Results reported in tables are for seven sets of values for  $\{\eta, \theta, \zeta, \mu\}$ . It was found that generally networks where there is no distance cost for the l-group, the network savings are the highest. For the networks considered here, the bigger network tends to save more than smaller network as far as comparison with static-

**Table 3** Results for various cost parameter values for EN-3

$\{\eta, \theta, \zeta, \mu\}$	DRDCR-cost	staticNet-Cost	% cost increase
{100,50,0,1}	23129544	29654760	28.21%
{100,75,0,1}	25043856	32282760	28.90%
{100,50,0,0.1}	8577343	10547076	22.96%
{100,50,1,1}	43476840	53926872	24.04%
{100,75,1,1}	45397080	56851272	25.23%
{100,50,0.1,1}	25270874	30885602	22.22%
{100,50,0.1,0.1}	10712822	12367317	15.44%

NetCost. We have observed as high as about 29% cost saving in our test cases.

## 5. Discussion

In this paper, we propose a two-level dynamic routing for broadband networks where dynamism is provided both at the call level and at the virtual path level. We then present a network dimensioning model for such an environment for forecasted load given for different hours during a day which takes into account dynamic reconfigurability of the VPs as well as dynamic call routing. For various cost parameter sets used in our computational studies, we found the network savings to be as high as about 29% compared to a network with static-VP configuration. We present our results for only three traffic classes; however, in future it is possible that there may be a large number of traffic classes. An obvious question is whether the model we presented is still applicable; the answer is affirmative from the theoretical standpoint as long as new functions  $d(., ., .)$  are determined for these emerging service classes. However, the size of the problem grows with more service classes – this would require more computational power and may put a limit on the use of CPLEX to solve sub-models (2) and (3). We see two possible ways to tackle this issue: (a) further development of algorithms to decompose sub-models (2) and (3) even further to make it manageable to solve, and (b) several traffic classes may be aggregated to form a ‘super’ service class for which a new estimation for demand requirement  $d(., ., .)$  needs to be developed – this process may lead to consideration of only a handful of super classes in model (1), in which case our present approach as given in section 3 still applicable. Nevertheless, this area requires further research.

It should be noted that the cost we have listed here is capital cost; to operate such a network to provide reconfigurability requires additional operational and development cost; determination of such cost is beyond the scope of the present paper.

We have mentioned in the introduction that DRDCR framework can be useful in case of network overload. For example in the event of a focused overload, certain switch node pairs may have significantly more traffic demands than they were originally fore-

casted for; this can result in higher connection blocking and also cell loss for the service classes for these switch pairs. To provide better load balancing and throughput, network rearrangement at VPC level may be necessary by seeking out capacity elsewhere in the network that has been underutilized by the other demand pairs; this can be another use for dynamic reconfigurability of VPCs – again, this area requires further investigation.

Finally, we have discussed dimensioning for CBR and VBR traffic in this paper. A broadband network may also carry other service classes than CBR or VBR traffic, such as unspecified bit rate (UBR) traffic. The question is: is it possible to accommodate UBR traffic in our framework? We believe it is. In the case of UBR traffic, we need to have some idea of traffic demand defined in terms of packets or cells per second for connections at certain time during the day from statistics collected in previous week/month; note that in this case we do *not* need know the behavior of each UBR connections. We can still use our framework by defining a service class for UBR traffic and creating a separate STQoS class and provide separate VPCs for this service class. Since, in our framework, different VPCs are non-statistically multiplexed in a transmission link, we don’t have to worry about UBR traffic interfering with real-time both CBR/VBR traffics on a link. It may, however, be necessary to provide partitioned buffering at switching nodes for different service classes. This is beyond the scope of the present paper to address the dynamics of switch buffering for different traffic classes. Nevertheless, as far as the network dimensioning is considered, our framework appears to be extensible to UBR traffic – more studies are obviously needed in this regard.

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- D. Medhi** received the B.Sc. (Hons.) in Mathematics from Cotton College, Gauhati University, Assam, India, M.Sc. in Mathematics from the University of Delhi, India, M.S. and Ph.D. in Computer Sciences from the University of Wisconsin–Madison, USA in 1981, 1983, 1985 and 1987, respectively. He is an Associate Professor in the Department of Computer Networking at the University of Missouri–Kansas City (UMKC), USA. Prior to joining UMKC, he was a Member of Technical Staff at the AT&T Bell Laboratories, Holmdel, New Jersey, USA from 1987 to 1989. His current research interests are in survivable network design, dynamic routing, broadband network design, large-scale optimization algorithms, network architecture and network management. He is a member of ACM, IEEE, INFORMS and SIAM. He is on the editorial board of *Journal of Network and Systems Management* and is a member-of-council of INFORMS Section on Telecommunications.
- C. T. Lu** received the B.S. in Computer Science from Tunghai University, Taichung, Taiwan in 1990. After serving two years in the military, he worked as a software engineer at Tecom Company, Taiwan and Cameo Company, Taiwan, before joining the University of Missouri–Kansas City, USA in 1994 to pursue the MS degree in Computer Science. He is completing his MS in CS with an emphasis in Networking in December 1996.